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Novel methods of characterizing heterogeneity inside the earth have been developed based on the theoretical study of wave propagation through complex media. Multiply scattered waveforms, for example from the "coda" regions of seismic records, can be used to characterize statistical properties of the heterogeneity. The approach used can accommodate strong multiple scattering, such that one is enabled to investigate the conditions under which the heterogeneity is so important that effectively no energy is transmitted forward by the seismic waves. Similar theoretical methods can be utilized to investigate diffusive processes through heterogeneous media, such as heat flow through the earth's crust. The seismological application is being tested on detailed measurements obtained from the KTB (the German very deep) borehole, with initial results appearing to be most promising.

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FINAL TECHNICAL REPORT
GRANT # F49620-92-J-0544

STATISTICAL INVERSION OF SEISMIC AND HEAT FLOW DATA

PRINCIPAL INVESTIGATOR PROF. RAYMOND JEANLOZ

The contract supported a multi-disciplinary research effort among geophysicists and theoretical physicists to evaluate new methods of characterizing heterogeneity of material properties inside the Earth. Most of the effort involved developing new theoretical techniques of using seismological and other geophysical observations to characterize the statistical variations of physical properties with location in the Earth. Rather than focussing on the forward problem of determining, for example, how heterogeneities in elastic-wave velocities causes scattering of seismic waves, the approach highlighted the use of inverse methods to investigate the amplitudes (waveforms) of multiply scattered waves.

The general approaches used are described in P. Sheng's monograph "Introduction to Wave Scattering, Localization and Mesoscopic Phenomena", which was written based in part on the work supported by this contract. The methodology can account for arbitrarily strong multiple scattering, such that one can investigate the conditions under which localization becomes significant; that is, the conditions under which the scattering is so strong that effectively no wave energy is propagated forward any more. This is an important consideration because it allows one to estimate the conditions under which information is fundamentally lost from the seismogram, for example.

The new applications have required further development of the theory, which has been pursued using diagram methods of field theory. Follow-up work has included developing software to implement the theory and to analyze actual data. An emphasis has been placed on modelling data from the German KTB hole, because this is the best documented deep coring of the Earth's crust available for study. Although application of the theory to inverting seismic waveforms from the KTB hole is straightforward in principle, data handling has been trickier -- hence much slower -- than anticipated because of technical difficulties including identifying and removing unreliable data (a problem that has plagued virtually all analyses of data from this borehole). The first round of analysis is nearing completion, and a major publication is in preparation by Z. Zhang and P. Sheng on the results of this work.

PUBLICATIONS

P. Sheng, "Introduction to Wave Scattering, Localization and Mesoscopic Phenomena" (Academic Press, San Diego : c1995).

Z. Zhang and P. Sheng, manuscript in preparation (1997)

Final Technical Report

AFOSR Grant 92-J-0544

R. Jeanloz
University of California, Berkeley

The grant supported an interdisciplinary research effort among physicists and geophysicists to develop new ways of characterizing the heterogeneity of the Earth's interior. The motivation for this work comes from the increasing recognition that geophysical observations, notably from seismology, can be significantly influenced by the presence of locally strong heterogeneities within the planet. For example, scattering appears to play a key role in the development of the seismic Lg phase, and the classical "Conrad Discontinuity" is widely attributed to varying degrees of quasi-coherent scattering rather than to the occurrence of a true structural or lithological boundary at mid-crustal depths. Strong scattering of seismic waves is also likely to take place due to the presence of heterogeneities deep in the mantle.

Our approach has been twofold: i) the use of forward modelling applied to field observations in order characterize the nature of heterogeneities in the Earth's crust; and ii) the development of inverse methods to extract information about heterogeneities and underlying (larger-scale) structures from seismological and other geophysical observations. As we are considering potentially strong heterogeneities that can give rise to complex multiple scattering phenomena, we apply formalisms that have been successfully developed for such problems in other research disciplines [1].

1) Characterization of Crustal Heterogeneity

The main difficulty in characterizing the spatial heterogeneity in the physical properties of the Earth's interior is to obtain an adequate sampling over distance scales that are sufficiently large to be useful. To this end, we have analyzed the density and seismic-wave velocity logs obtained from the KTB deep borehole in Germany. The data provide the longest sequence of high-quality petrophysical measurements now available, representing an essentially continuous sampling over a depth interval of nearly 6 km into the crust (Fig. 1). Also, the KTB borehole transects deformed metamorphic units typical of mid- to lower-continental crust, and is therefore highly relevant for obtaining a picture of large-scale heterogeneity underlying many seismic stations around the world.

The autocorrelation of the density (ρ), longitudinal velocity (V_P) and transverse velocity (V_S) logs with depth (z) can each be fitted with exponential functions, $\exp(-\Delta z/d)$ where Δz is the depth lag and d is a decay (decorrelation) length. The resulting values of d, 5.3 m for the density and 2.2 m for both velocities, is in good accord with what has been independently found for the KTB logs.

It is remarkable that similar decay lengths of the order of meters are obtained from entirely different rock sequences [2]: records sampled in different parts of the world and representing completely different lithologies (for example, from "layer-cake" sedimentary sequences as opposed to the high-grade metamorphic units of the KTB borehole). Why such a wide variety of crustal rock distributions tend to exhibit similar decorrelation lengths is a basic question that remains unanswered; it appears to be related to the "memory" inferred from Markov analyses of stratigraphic sequences, which has yet to be satisfactorily

explained after years of study [e.g., 3]. Indeed, our study reveals new aspects of the stratigraphic "memory" effect that can help to explain this phenomenon.

In order to translate what the detailed KTB logging measurements of heterogeneity imply for seismic records, we have extended a theoretical analysis that has been successfully developed for characterizing the scattering of scalar and electromagnetic waves [4]. Specifically, we wish to quantify the scattering of seismic waves by the heterogeneities in velocities and density (or impedances), even if over distances *larger* than the sample lengths obtained from the KTB borehole.

To begin, we focus on a single parameter, the localization length ξ_c which provides a measure of the distances over which strong scattering becomes dominant. In one dimension, the localization length for seismic waves can be thought of as the distance over which backscattering has effectively blocked any forward transmission of elastic energy. In two and three dimensions, it provides a distance scale within which strong (multiple) scattering characterizes the seismic-wave propagation [cf. 5].

For a given propagation distance, L, the transfer-matrix method can be used to calculate the transmission spectrum $T(\omega)$ as a function of frequency (ω) from the density and velocity logs, thereby yielding estimates of the frequency-dependent localization length $\xi(\omega)$ [4]. Specifically, when L is on the order of $\xi(\omega)$ for an infinite medium, $T(\omega)$ exhibits resonant-like behavior; near the resonance frequency, ω_r, $T(\omega)$ takes on a Lorentzian shape with half-width $\Delta\omega_r$. Associating the dwell time $\Delta\omega_r^{-1}$ with a diffusion time for energy transport ultimately yields the localization length

$$\xi(\omega_r) = a\,\Delta\omega_r\,L^2\,v^{-1} \qquad (1)$$

where $a \approx 1.5$ is a constant [4]. In (1), v is the effective medium wave speed given by

$$v^{-2} = \langle \rho(z)/M(z) \rangle \qquad (2)$$

where M is either the longitudinal or shear modulus for, respectively, P and S waves, and the brackets indicate an average over depth, z.

The localization length at each resonant mode of the transmission spectrum is numerically calculated as an average over a small frequency interval, with the results for the V_P and V_S logs of the KTB borehole being shown in Figs. 2 and 3. As frequencies approach the typical seismic band it is clear (for the S waves in particular) that values of ξ reach 10-20 km, which is well in excess of the length of the original velocity log. The important point here is that a method has been developed to accurately calculate the localization length from a single finite-length configuration; this is equivalent to accurately evaluating the multiple scattering loss from a single configuration. Hilbert transformation yields the fluctuations of wave velocities as a function of frequency from the localization-length spectra [4].

Thus, it is possible to obtain quantitative data about the effects of heterogeneities over distance scales approaching those relevant to problems in seismic-wave propagation through the crust and mantle. It is evident based on direct logging measurements that strong (multiple) scattering can have a significant influence over distances of tens of km, and therefore cannot be ignored in general. It is worth noting, in this regard, that the original velocity and density logs do not exhibit particularly large or anomalous fluctuations with depth (Fig. 1). Therefore, we expect that scattering effects due to heterogeneities in physical properties can be locally much stronger within the Earth's crust or mantle than we have inferred from the more "typical" variations evident from the KTB well logs.

2) *Inverse Modelling of Strongly Scattered Seismic Waveforms*

We examine strong scattering (e.g., at high-frequencies) as a model problem in order to determine how much information can be extracted from a seismic waveform representing transmission through a very heterogeneous medium. The underlying analysis stems from inversion methods described elsewhere, specifically using White's "W Equation" [e.g., 6, 7].

To give a flavor of what can be done, we consider a medium having a smooth, large-scale velocity variation of 0.5 (Fig. 4) on which is superimposed a random small-scale heterogeneity having a variance of 0.3 (Fig. 5); all units are non-dimensionalized in this analysis. The degree of heterogeneity is considerably larger than is the case with the KTB data, and its effect on seismic waveforms is illustrated by evaluating the propagation of a Gaussian pulse through both the smooth and heterogeneous model media (Fig. 6). This case actually provides a conservative view, in that a Ricker pulse (for example) exhibits roughly 3 orders of magnitude greater effect of scattering on the amplitudes due to the presence of higher-frequency components in the underlying waveform than is the case with the Gaussian pulse.

The inversion involves applying a layer-peeling algorithm in order to extract the large-scale velocity structure that is essentially buried in the signal due to the effects of multiple scattering. By necessity, the small-scale heterogeneities are modelled assuming a Gaussian spectrum. From analyses of real rock sequences, as described above, there is reason to suspect this assumption. Further studies of actual rock sequences, as well as of recordings of seismic waves after propagation through strongly heterogeneous regions of the Earth, will be required in order to go beyond this assumption.

An example of how well the inversion scheme works is illustrated in Fig. 7, which summarizes results assuming mismatched (A) and pressure-release (B) boundary conditions as compared to the actual model variation of velocity (C) (again, results are shown in non-dimensional form, plotted here with a change of axis). It is evident that the case assuming mismatched boundary conditions yields a better inversion than the pressure-release case. The reason for this difference has to do with the treatment of higher frequencies in the latter case.

Although the model of heterogeneity examined here is admittedly idealized, it is worth noting that the magnitude of the velocity fluctuations is much greater than is normally considered in seismology. Thus, although the inversion scheme is still at a rudimentary stage, it clearly shows the potential for extracting information about large-scale structure even from waveforms that appear to be dominated by "noise" due to multiple scattering caused by significant small-scale heterogeneities.

3) *Analyses of Non-seismological Data*

We have initiated studies of three other types of geophysical measurements that may complement seismological determinations of structural heterogeneity within the Earth. First, we have been pursuing both forward and inverse models of electromagnetic propagation into the crust. The objective is to make a link between traditional finite-element methods, which describe the crustal structure in terms of homogeneous blocks, and the scattering approach explored above [e.g., 1, 4]. The motivation for this work is that considerable information is available from electromagnetic studies of shallow crustal structures. Moreover, because of the wide frequency range that is sampled (typically ≥ 2-3 orders of magnitude wider than the seismic data), there is a possibility of obtaining a better characterization of the spectrum of localization lengths.

Second, because the scattering approach can be applied to diffusive processes as well as wave propagation [1], we have been examining the use of heat-flow measurements as an added constraint on the nature of large-scale heterogeneities in rock types throughout

the crust. It is well known that regional heat flow measurements can be interpreted in terms of heterogeneities in thermal properties (either or both heat production and thermal diffusivity) throughout the crust [e.g., 8]. Although the analysis is in progress, it appears quite possible to extend previous analyses, which have necessarily assumed weak scattering, to more realistic conditions of strong heterogeneity. The advantage over seismic observations is that there tends to be an averaging over the smallest spatial scales, such that one has a hope of getting a clearer picture of the intermediate scale of heterogeneity in structure.

Finally, we have explored the potential application of an entirely novel method of geophysical observation, neutrino absorption spectroscopy which in the future may provide independent constraints on the Earth's internal structure [9]. Motivated by the current development of "observatories" (detector arrays) intended to record high-energy (~TeV-PeV) neutrinos from astrophysical sources, we have developed methods of imaging large-scale features of Earth structure that complement seismological methods. In particular, neutrino absorption depends on density (average nucleon number) with a spatial resolution and precision that should be comparable to the seismological constraints (i.e., from normal modes). Furthermore, the energy dependence of neutrino absorption can potentially be used to obtain compositional information about the Earth's interior (variations in mean atomic weight), thereby significantly enhancing current means of interpreting seismological observations. As the detector arrays are only beginning to become operational, our study anticipates a new method of geophysical imaging that is could become important in the coming decade or two.

4) Summary

Our investigations of heterogeneity inside the Earth depart from the traditional methods of geophysical imaging, which assume that the planetary interior can be described as an aggregate of homogeneous volumes. Instead, we focus on the intrinsic spatial variability of material properties inside the Earth, allowing for the possibility of strong heterogeneity causing multiple scattering and related phenomena such as wave localization. The objective is both to characterize the real (heterogeneous) structure of the Earth and to understand the causes of wave arrivals and other phenomena not anticipated from the classical deterministic models of the interior: e.g., refractions caused by variations in correlation lengths or other measures of heterogeneity, rather than actual lithological structure. Analyses of geophysical observations from the KTB borehole and elsewhere demonstrate that heterogeneity is realistically significant enough that it cannot be ignored. The theoretical foundation required to treat these effects is developed, with extensions to higher dimensions (1- and 2-D to 3-D) and from scalar- to vector-wave equations (e.g., including conversions) having been derived in principle.

Further applications are promising. The most important avenues to pursue include carrying out additional studies of detailed geophysical observations comparable to those of the KTB borehole described above. Anisotropies in localization length must be considered, as must alternative means of quantifying the heterogeneity. It is only in this way that the true structural heterogeneity of the interior can be characterized, as there is little point in devising models of the Earth's heterogeneity unless they agree with observations. Additional theoretical work is required to enhance the inversion approaches described above: make them less dependent on simplifying approximations, as noted above, and test them rigorously against real data. It is also necessary to identify the more global or qualitative phenomena induced by heterogeneity that could be recognized in seismological and other geophysical observations. For this reason, further attempts at simultaneously analyzing (or inverting) several types of geophysical data sets from one area (e.g., seismological, electromagnetic, etc.) appear to be especially promising.

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FIGURE CAPTIONS

Fig. 1 P- and S-wave velocity logs as a function of depth, $V_P(z)$ and $V_S(z)$ in km/s, for the KTB deep borehole in Germany.

Fig. 2 P-wave localization length as a function of frequency, $\xi_c(\omega)$ in m, obtained from the KTB deep borehole logs (Fig. 1).

Fig. 3 S-wave localization length as a function of frequency, $\xi_c(\omega)$ in m, obtained from the KTB deep borehole logs (Fig. 1).

Fig. 4 Large-scale (smooth) variation in wave velocity as a function of depth, $<c(z)>$ in nondimensional units, assumed for the inversion model problem.

Fig. 5 Variation in wave velocity as a function of depth, $c(z)$ in nondimensional units, assumed for the inversion model problem. The wave velocity is given by a short-scale variance of 0.3 superimposed on the large-scale structure of Fig. 4.

Fig. 6 Wave amplitude as a function of time, $w(\tau)$ in nondimensional units, assuming a Gaussian pulse that has been propagated through the smooth structure of Fig. 4 (heavy curve) and through the heterogeneous structure of Fig. 5 (crosses and thin curve).

Fig. 7 Smooth velocity anomaly, $\Delta<c(z)>$ in nondimensional units, recovered from a Ricker pulse that has been propagated through the heterogeneous structure (Fig. 5) assuming either mismatched (A) or pressure-release (B) boundary conditions. For comparison, the actual structure is given by curve C.

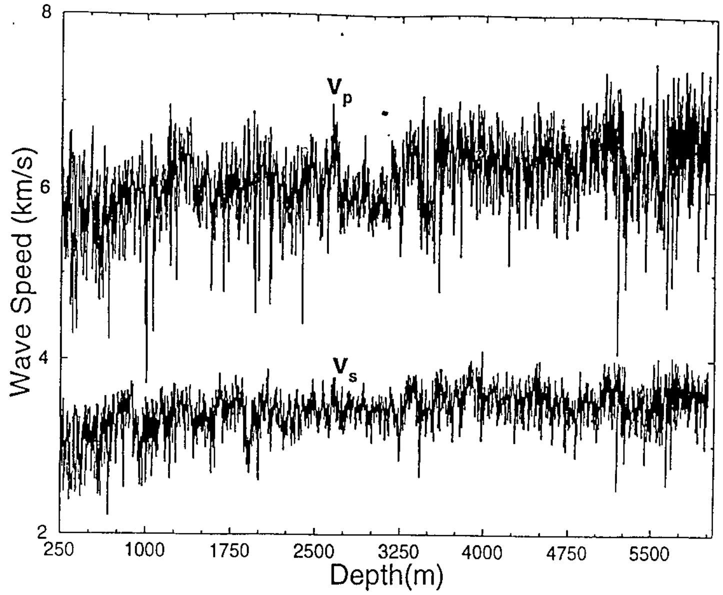


Fig. 1

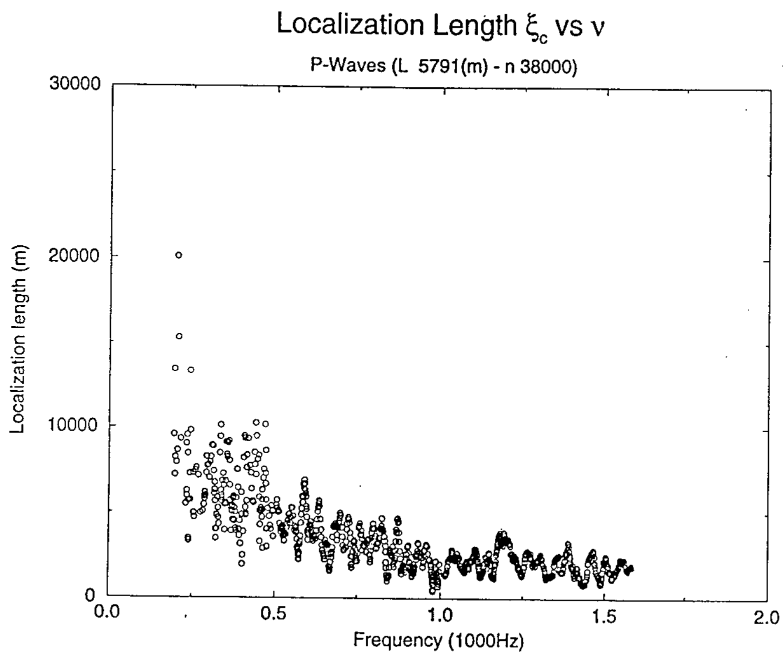
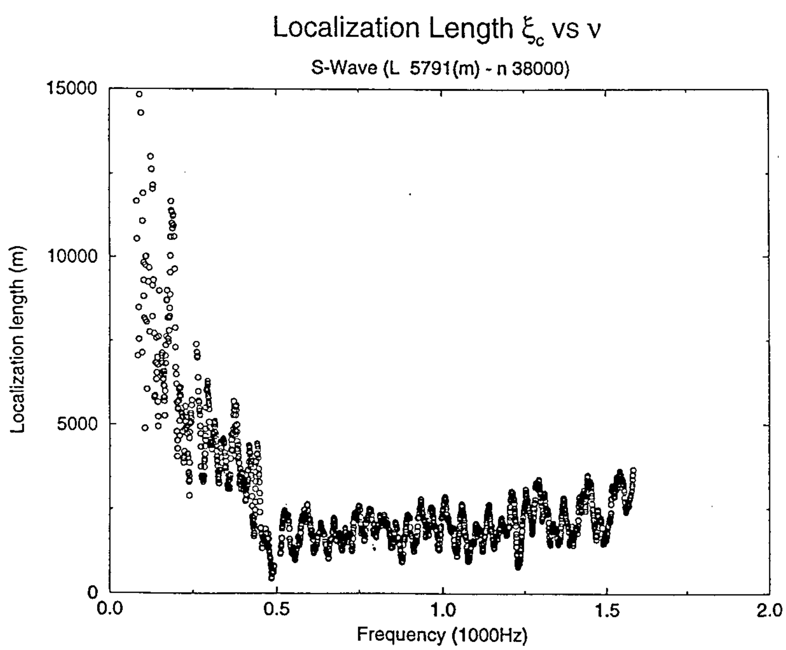


Fig. 2



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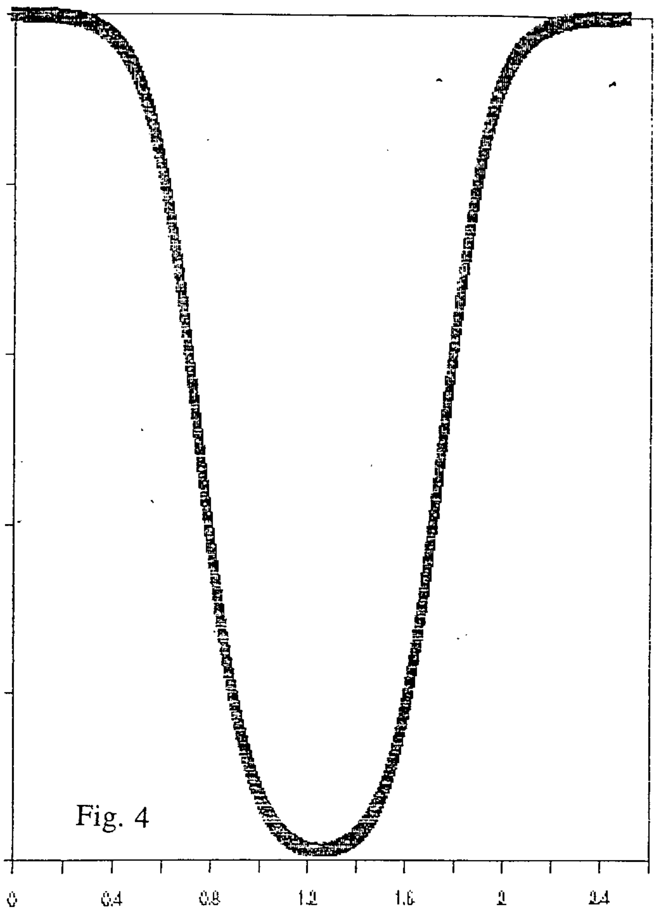

Fig. 4

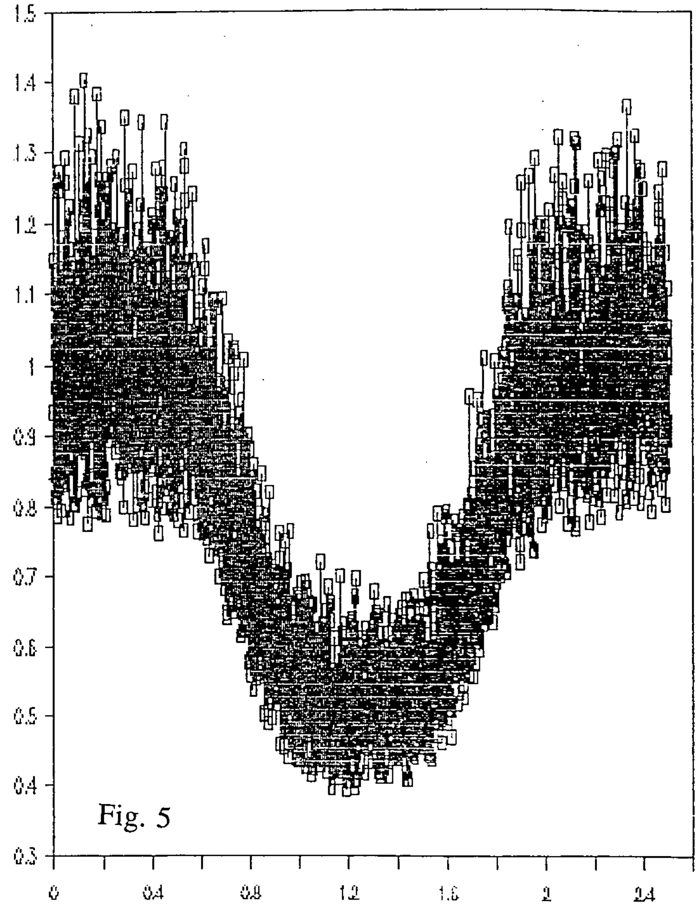

Fig. 5

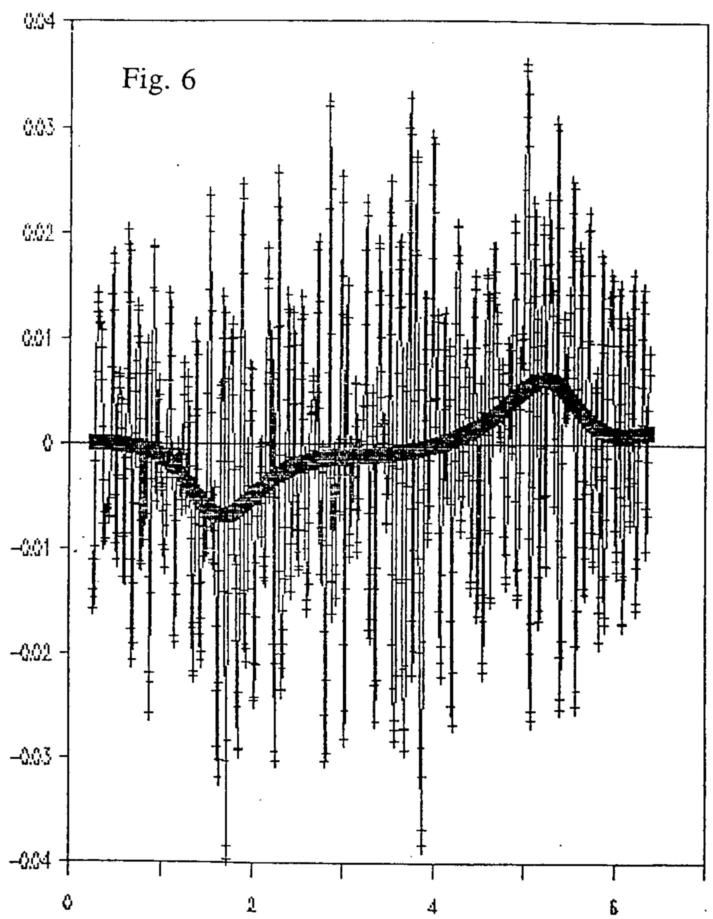

Fig. 6

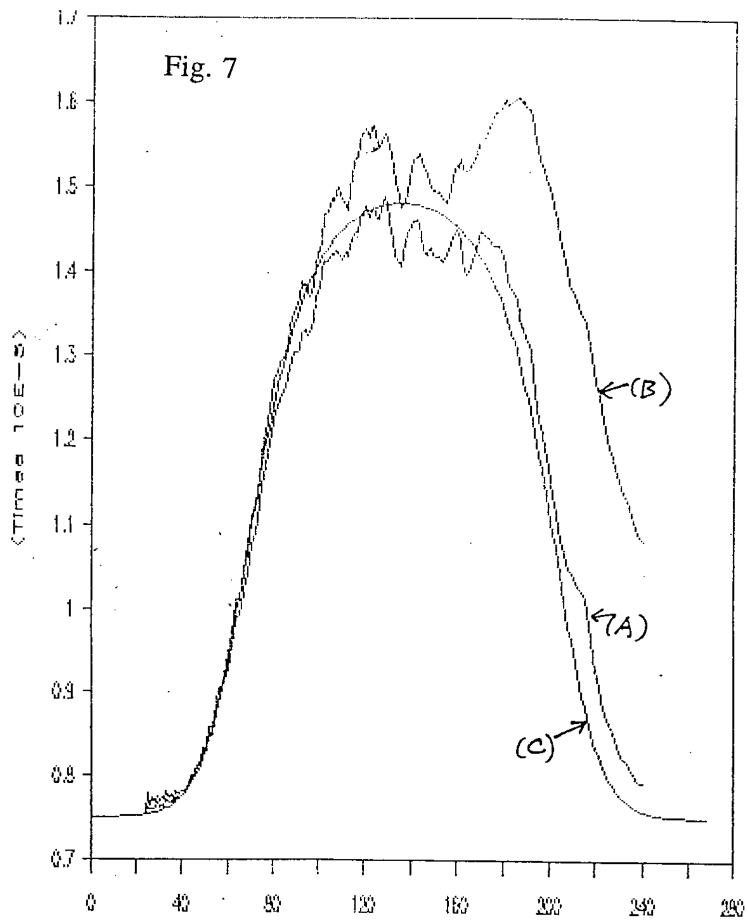

Fig. 7